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Conceptual framework for balancing society and nature in net-zero energy transitions

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ABSTRACT

Transitioning to a low carbon energy future is essential to meet the Paris Agreement targets and Sustainable Development Goals (SDGs). To understand how societies can undertake this transition, energy models have been developed to explore future energy scenarios. These models often focus on the techno-economic aspects of the transition and overlook the long-term implications on both society and the natural environment. Without a holistic approach, it is impossible to evaluate the trade-offs, as well as the co-benefits, between decarbonisation and other policy goals. This paper presents the Energy Scenario Evaluation (ESE) framework which can be used to assess the impact of energy scenarios on society and the natural environment. This conceptual framework utilises interdisciplinary qualitative and quantitative methods to determine whether an energy scenario is likely to lead to a publicly acceptable and sustainable energy transition. Using the SDGs, this paper illustrates how energy transitions are interconnected with human development and the importance of incorporating environmental and socio-economic data into energy models to design energy scenarios which meet other policy priorities. We discuss a variety of research methods which can be used to evaluate spatial, environmental, and social impacts of energy transitions. By showcasing where these impacts will be experienced, the ESE framework can be used to facilitate engagement and decision-making between policymakers and local communities, those who will be directly affected by energy transitions. Outputs of the ESE framework can therefore perform an important role in shaping feasible and energy transitions which meet the Paris Agreement targets and SDGs.

1. Introduction

In 2015, the Paris Agreement and the 2030 Agenda for Sustainable Development set transformative implications for global development and sustainability (Gomez-Echeverri, 2018; Castor et al., 2020). The Paris Agreement aims to keep global temperature rise this century below 2 °C above pre-industrial levels and to pursue efforts to limit this temperature increase to 1.5 °C (UNFCCC, 2015). A target of 1.5 °C will only be achieved if significant reductions of greenhouse gas (GHG) emissions are made, which implies a worldwide transition to net-zero by the mid-century (Rogelj et al., 2015). Simultaneously the 2030 Agenda introduced 17 Sustainable Development Goals (SDGs), with 169 sub-targets relating to global challenges including: climate change, environmental degradation, biodiversity loss, justice, poverty and inequality (Banister, 2019; Cadez et al., 2018; Küfeoğlu and Khah Kok Hong, 2020; Yildiz, 2019). Together these frameworks provide a

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blueprint towards a sustainable, low-carbon and more equitable world.

Both the Paris Agreement and SDGs acknowledge the criticality of developing sustainable energy systems to address the environmental, economic and societal challenges of climate change (Phillis et al., 2020). Energy systems are intrinsically linked to the natural environment and human wellbeing: it is therefore imperative that decarbonisation is not tackled in isolation (Fuso Nerini et al., 2018). For example, if siloed thinking prevails, we could witness the adoption of energy scenarios that achieve net-zero targets but lead to the loss of threatened plant and animal species, or which generate or widen existing inequalities in society (Holland et al., 2019; Sovacool et al., 2015). To avoid the unintended consequences of siloed policymaking, it is imperative that decision-makers adopt a more holistic approach to energy transitions in the coming decades.

In this paper, we present the Energy Scenario Evaluation (ESE) framework which has been developed to assist policymakers and researchers in evaluating the sustainability and public acceptability of energy scenarios. The framework uses a mixed method approach to evaluate energy scenarios based upon criteria which have been developed from the SDGs. We aim to demonstrate how an interdisciplinary approach can be used to support policymakers developing energy scenarios that consider a wider set of sustainability criteria. The framework can help stakeholders identify the opportunities and challenges in future energy scenarios, from a wide range of perspectives. In addition, the framework can be used to explore future avenues for incorporating environmental and socio-economic data into energy models to support the creation of energy scenarios which are reflective of a broad range of impacts.

No other framework exists which combines multiple quantitative and qualitative methods to evaluate energy scenarios against public acceptance and sustainability criteria. Such a framework is needed to explore the wider context of energy scenarios, which are produced by energy models that typically focus on techno-economic factors (Jebaraj and Iniyan, 2006; Strachan et al., 2009). Energy models have been influenced by a limited number of SDGs such as: economic growth (SDG 8), industrialisation (SDG 9), climate action (SDG 13), and foreign investment (SDG 17) (e.g. Daly and Fais, 2014). Other environmental, social and political considerations of energy systems are often overlooked (Schuitema and Sintov, 2017; Thormeyer et al., 2020). Only a limited number of studies have explored the trade-offs and opportunities that exist between the SDGs and decarbonising energy systems (e.g. Fuso Nerini et al., 2018). The majority of existing energy models have not been designed to engage with the high temporal and spatial nature of renewable energy generation (Pfenninger et al., 2014). As a result, energy scenarios do not consider spatially dependent factors such as land use requirements and environmental impact (Dockerty et al., 2014; Bolton and Foxon, 2015; Holland et al., 2018; Thormeyer et al., 2020). In recent years, a limited number of studies have explored the role of high temporal and spatial resolution in energy modelling (e.g. Price et al., 2018; Zeyringer et al., 2018; Tröndle et al., 2020). It is clear however that coupling technological and socio-economic perspectives is necessary to identify technically feasible, financially viable, and socially equitable transition scenarios (Patrizio et al., 2020; Hooper et al., 2018). Low-carbon energy transitions need to consider the trade-offs and complex interactions highlighted by the energy quadrilemma; the need to balance cost, the environment, energy security and job opportunities (Olabi, 2016).

1.1. What is a sustainable, publicly acceptable energy transition?

Energy scenarios are created to explore how countries may navigate the transition to a low-carbon energy system. For the purpose of this paper we define '*energy transition'* as a fundamental and systematic change to the existing energy system (Parag and Janda, 2014; Sovacool, 2016). An energy transition generally involves a transformation within the energy system, usually to a particular fuel source (i.e. from wood to coal), technology (i.e. internal combustion engines to electric) or prime mover (i.e. a device that converts energy into useful services) (Hirsh and Jones, 2014; Miller et al., 2015; Sovacool, 2016). Energy transitions are expected to have a considerable impact on the current energy system, with impacts and changes to the planning and operating paradigm, market structure and regulatory frameworks (Berjawi et al., 2021). The progress of this transition depends on multiple parameters and variables, including key stakeholders (including civil society groups, the media, local communities, political parties, and policymakers) and the circumstances that open up new paths and opportunities for change (Geels et al., 2017; Kern and Rogge, 2016; Sovacool, 2016). Globally, we are currently witnessing the next energy transition with the rapid expansion of renewable energy sources (IRENA, 2021), this transition will require a holistic and interdisciplinary approach to ensure this energy transition does not negatively impact society or the environment (Crnčec et al., 2021; Mitrova and Melnikov, 2019).

Decarbonising our carbon intensive global energy system is of critical importance: it is currently considered unsustainable based on a wide range of social, economic, and environmental criteria (Riahi et al., 2011; Grubler, 2012). To cover the wide range of impacts that an energy transition can have, we define sustainability in the broadest terms, those which are reflected in the 17 SDGs. We define a sustainable energy scenario as one that meets 'the needs of the present without compromising the ability of future generations to meet their needs' (World Commission on Environment and Development, 1987). We assume this is one which meets both economic, environmental and social objectives. As discussed by Moldan et al. (2012), although indicators can be used to determine whether sustainability targets are being met, it is difficult to define exactly what a sustainable future looks like. It is less whether an absolute value has been met, rather the notion that we are heading in the right direction (Moldan et al., 2012). This perspective is incorporated into the ESE framework to consider the complexity of what sustainability actually means.

When determining the feasibility of an energy scenario, policymakers should pay close attention to public attitudes around the transition to net-zero. A successful energy transition requires engagement with the public: the public often see things missed by experts, add legitimacy to the transition process, and have a democratic right to be involved in decision-making (Fiorino, 1990; Szulecki, 2018). Public acceptance of an energy transition operates at different scales, with support at the broad socio-political level not necessarily translating to acceptance for a particular project at the community level, where factors including trust and justice are relevant (Wüstenhagen et al., 2007). For example, although support for wind farms in many countries is high at the national level, public acceptance at a local level is mixed (Rand and Hoen, 2017). Policymakers therefore need to be able to communicate appropriate information when they are engaging with the public.

Public support for an energy technology or project is not static but rather can grow or fall over time; the 'social licence to operate' (SLO) refers to the ongoing community and stakeholder acceptance of a particular technology or project (Prno, 2013). Key components of establishing a SLO include forming relationships with stakeholders, communicating impacts of the project with the local community, and addressing sustainability concerns (Prno, 2013). The ESE framework provides the opportunity to address these core elements of the SLO: whereby public attitudes and preferences can be integrated into the design of energy scenarios, and spatially resolved environmental and social outputs can be used to provide information to local communities, facilitating holistic decision-making. This approach should prevent the implementation of energy technology in 'top-down' or 'place-blind' ways, both of which are likely to provoke public opposition and failure to achieve a SLO (Goldthau, 2018; Buck, 2018; Burke and Stephens, 2018). Several recent studies have highlighted the importance of engaging with local communities and stakeholders during energy transitions to mitigate the risk of not achieving public backing or a SLO (Moffat et al., 2016; Baumber, 2018; Hurst et al., 2020; Sovacool et al.,

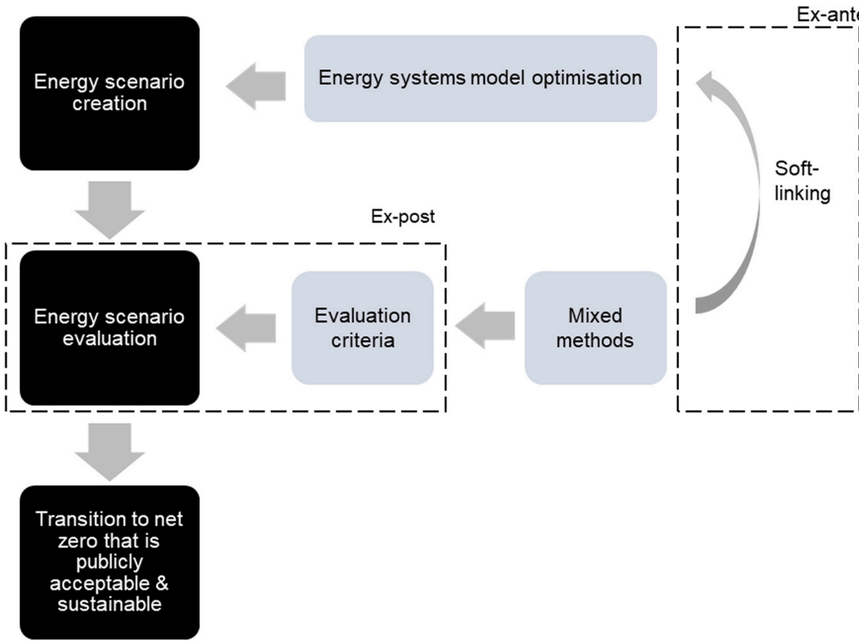

Fig. 1. Overview of the Energy Scenario Evaluation (ESE) framework.

2019; Roddis et al., 2018). The SDGs were designed not only for policymakers but also for engagement with the public, and to promote sustainability (United Nations, 2019). Energy system transitions which are designed to meet the SDGs, and where this connection is explicitly made, therefore presents the opportunity for clearer communication with the public, which could support public acceptance of energy system changes. Additionally, meeting the broad criteria of sustainability encapsulated by the SDGs will demonstrate sustainability in environmental, economic, and social terms. This too could be important for public acceptability, given public concern that there may be trade-offs between environmental sustainability and economic sustainability (Bain et al., 2019).

The SLO concept is related to and interconnected with that of energy justice. Energy justice is a conceptual framework which explores how the costs and benefits of an energy transitions are distributed amongst society and how stakeholders are engaged in the decision-making process (Boardman, 2013; Bullard, 2005; Heffron et al., 2015; Heffron and McCauley, 2014; Jenkins et al., 2016, 2021; Lee and Byrne, 2019; Liddell and Morris, 2010; Pastor et al., 2001; Sovacool and Dworkin, 2015; Walker, 2009; Walker and Day, 2012). The ESE framework touches upon these elements of energy justice but does not, and cannot, fully cover the theory of energy justice. Instead, we argue that the ESE framework should be used alongside processes which are centred upon energy justice and can delve into the complex layers of the framework, such as the work of climate assemblies (Climate Assembly UK, 2020).

1.2. Evaluating energy transitions using mixed methods

Despite the increased use of qualitative research methods in exploring energy transitions, there remains a lack of studies which integrate these methods with the quantitative approaches traditionally used in energy systems models (Royston and Foulds, 2021). Current policymaking is still heavily influenced by the output of quantitative energy models, often overlooking the value of qualitative methods. This is despite the limitations of focusing purely on quantitative or qualitative methods having been well documented, with a mixed methods approach widely advocated to help expand our understanding of the phenomenon being studied (Lieber and Weisner, 2010; Pluye and Hong, 2014; Almalki, 2016). For example, economic and natural science modelling are unable to fully consider the complexities associated with public acceptability of integrating low-carbon energy infrastructure across different spatial scales. The ESE framework that we propose provides a range of mixed methods to holistically assess energy system transitions, identifying how they can achieve sustainability as set out across the SDGs, as well as public acceptance of these transitions. This approach will allow researchers and policymakers to identify and explore the trade-offs and co-benefits that exist within energy scenarios to transition the economy to net-zero emissions. The SDGs are used conceptually as a means to evaluate energy scenarios and communicate their potential impacts to both decision-makers and the general public.

This article is structured as follows: Section 2 provides the rationale of the ESE framework and is split into four sub sections. Section 2.1 provides an overview of the framework, Section 2.2 defines the evaluation criteria and Section 2.3 details how the framework can be used to evaluate energy scenarios. Section 2.4 explains how the outputs of the framework could be soft-linked to energy models to improve their consideration of environmental and social factors. Section 3 discusses the key strengths (Section 3.1) and challenges of using a mixed methods approach within the ESE framework (Section 3.2). Section 4 details the key conclusions of the paper and the need for the ESE framework for policymakers and decisionmakers.

2. The Energy Scenario Evaluation (ESE) framework

2.1. Overview of framework

The ESE framework has been developed to assist policymakers evaluate whether energy scenarios can be considered as likely to be sustainable and publicly acceptable based on a range of evaluation criteria informed by the SDGs. The framework aims to (i) identify the ways in which existing energy scenarios impact society and the natural environment; (ii) use quantitative and qualitative tools to measure and assess these impacts; (iii) show how environmental and socio-economic data can be integrated into energy models to generate energy scenarios; and (iv) support decision-makers to identify and shape energy scenarios that achieve public acceptance and sustainability as conceived through the SDGs.

The ESE framework provides a holistic appraisal of energy scenarios designed to meet climate change targets. By incorporating a variety of interdisciplinary methods, our framework provides an insight into how

Fig. 2. Mapping direct evaluation criteria used within the Energy Scenario Evaluation (ESE) framework to meet the Sustainable Development Goals.

energy scenarios impact both society and the natural environment. The framework provides both an ex-post and ex-ante perspective on the development of energy scenarios (Fig. 1). Firstly, an ex-post perspective is used to explore whether an *existing* energy scenario would likely lead to a publicly acceptable and sustainable energy transition using a wide spectrum of evaluation criteria. An ex-ante approach is then used to identify how public acceptance and sustainability could be embedded within the energy systems models that generate the energy scenarios. This could, for example, include soft-linking the outputs of other interdisciplinary methods into energy systems models (Fig. 1). Various research methods could be applied within the ESE framework to evaluate energy scenarios; within Appendix Table A.1 we suggest various research approaches that could be particularly helpful.

2.2. Evaluation criteria

The evaluation criteria proposed by the ESE framework spans multiple disciplines from the social sciences (e.g. geography, sociology, and economics) to the natural sciences (e.g. biology, ecology, and chemistry) and engineering. Fig. 2 shows how the criteria are directly linked to the SDGs, illustrating how energy transitions are interconnected to human development.[1] As highlighted by previous studies however, there are multiple direct and indirect linkages between all 17 of the SDGs (Dawes, 2020; Zhang et al., 2016; Zhao et al., 2021). For example, Cernev and Fenner (2020) discussed that through the development of resilient infrastructure (SDG 9), enhancements can be made to water (SDG 6) and energy (SDG 7), leading to improvements in wellbeing (SDG 3), education (SDG 4), gender equality (SDG 5), sustainable cities (SDG 11), as well as improving economic growth (SDG 8). Therefore, it is important to have an awareness of the interactions and feedback between the SDGs as they can impact other SDGs either directly or indirectly (Zhang et al., 2016). Public acceptance is assumed to be based on an amalgamation of all of the evaluation criteria used in this study; with no one criteria able to define what it means to be publicly acceptable.

Mapping the evaluation criteria helps to identify the opportunities and challenges present in energy transitions (Fuso Nerini et al., 2018). The methods proposed within this framework provide an insight into the geospatial issues associated with energy transitions. The deployment of new renewable energy technologies will result in land use change which will have implications for the sustainable management, conservation and protection of marine, coastal, freshwater and terrestrial ecosystems (SDG 6, 13–15). By exploring geospatial issues, the framework can improve policymakers' understanding of how energy scenarios could impact biodiversity, food production, human health and wellbeing (SDG 2, 3, 15).

In addition to land use change, it is also important to consider the wider impacts of the energy transition on the economy. Using the energy transition to promote sustained, inclusive and sustainable economic growth (SDG 8) will influence other sectors including transport and industry. For example, if individuals transition away from relying on personal vehicles to using public transport, air quality could be improved and sustainable infrastructure developments supported, both of which can improve individual health and well-being (SDG 3, 11, 12). On the other hand, energy transitions may promote sustainable industrialisation and foster innovation through encouraging difficult to decarbonise economic sectors to adopt low carbon processes (SDG 9, 12).

[1] This paper has focused upon the SDGs most relevant to energy transitions within developed countries.

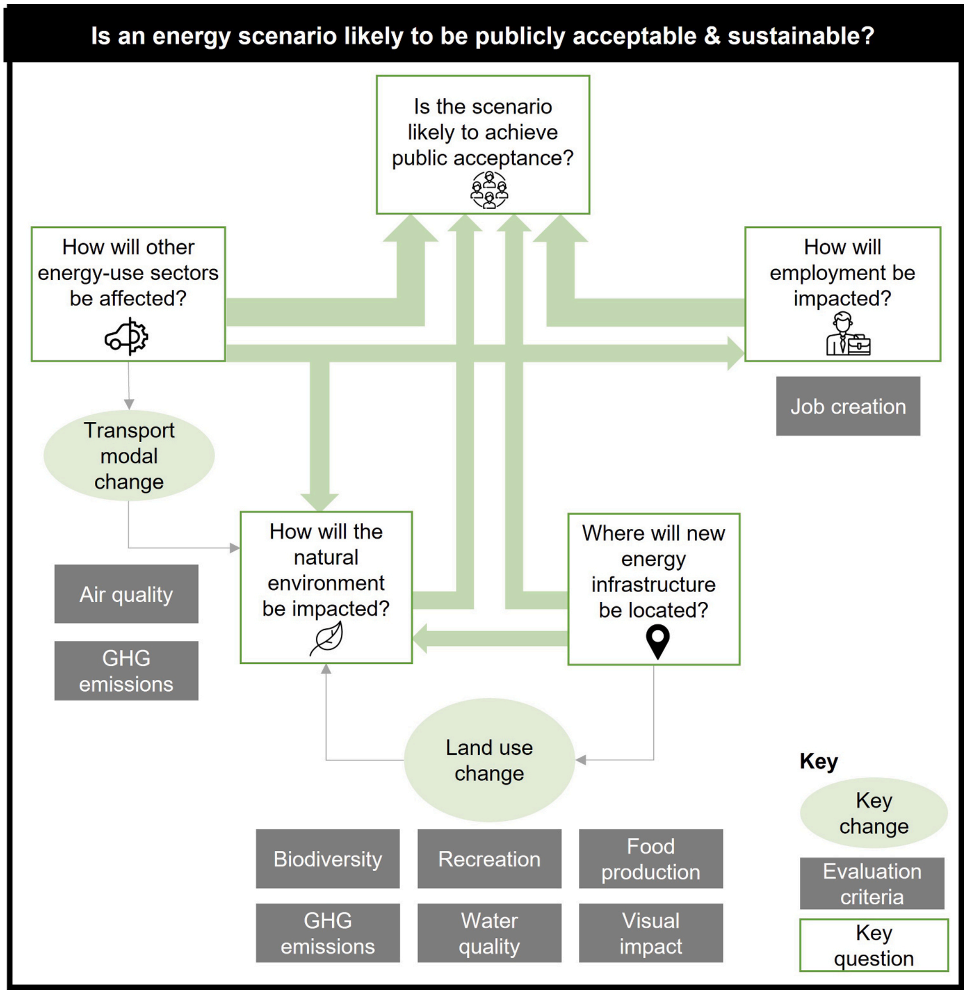

Fig. 3. An overview of the key changes, evaluation criteria and key questions addressed and interlinked within the Energy Scenario Evaluation (ESE) framework to better understand whether an energy scenario is likely to achieve public acceptance and sustainability.

2.3. *Ex-post evaluation*

To understand the public acceptance and sustainability implications of an energy scenario, the ESE framework sets out five questions key to the net-zero energy system transition, and the evaluation criteria and interdisciplinary methods which can be used to answer them. Fig. 3 shows how the five key questions are interconnected and the evaluation criteria used to answer each one. Appendix Table A.1 details all the methods suggested in this section. The five questions to evaluate an energy scenario are as follows:

1. Where will new energy infrastructure be located?
2. How will the natural environment be impacted?
3. How will other energy-use sectors be affected?
4. How will employment be impacted?
5. Is the scenario likely to achieve public acceptance?

The first question this framework addresses is the spatial distribution of new energy infrastructure. An energy scenario's impact on the natural environment and society will be strongly dependent on the spatial context of its infrastructure (Calvert et al., 2013; Howard et al., 2013). Multiple methods can be used to determine where energy infrastructure might be located including: spatial optimisation, predictive classification models, and inferential logistic regression (Delafield, unpublished; Donnison et al., 2020; Dunnett et al., 2020). Comparing the outputs of different methods allows policymakers to explore the sensitivity of different methodological assumptions. Some proposed methods which determine where new energy infrastructure might be located also consider the second question: how will the natural environment be impacted? Various methods exist to assess the impact of energy infrastructure, and its associated land use change, on food production and a myriad of ecosystem services including: mitigation of flooding, recreation benefits, carbon sequestration, GHG emissions, visual impact and biodiversity benefits (Appendix Table A.1). Additional methods can be applied to explore specific environmental impacts in depth, for example viewshed analysis could be used to determine the visual impact of an energy scenario at a local level (Carver and Markieta, 2012; Calvert et al., 2013; Wen et al., 2018).

To further explore the sustainability implications of an energy scenario, it is important to consider how other sectors will be impacted. The energy supply sector and resultant installation of new energy infrastructure is not the only way an energy scenario impacts the environment, changes to sectors including transport and industry can do so too. For example, changes to the transport sector will affect both GHG emissions as well as air quality. Methods that include high spatial resolution are needed to explore how an energy scenario's ratio of battery electric vehicles to conventionally fuelled vehicles will impact local air quality and consequently human health (Woodcock et al., 2009). Appendix Table A.1 details a data mining method which estimates the spatial distribution of traffic flows and subsequent air pollution at street (Sfyridis and Agnolucci, 2020, 2021). At a national level, the GHG implications of changes to transport and industrial processes will have been estimated during the creation of the energy scenario. As these sectors have been classified as hard to decarbonise, this framework highlights the importance of exploring the accuracy of the emission reductions included in an energy scenario (Agnolucci and Arvanitopoulos, 2019). Appendix Table A.1 details the operating emissions and panel regression analysis methods which can be used to do this (Agnolucci and Arvanitopoulos, 2019; Logan et al., 2020a, 2020b, 2020c, 2021).

Another aspect of how energy scenarios can impact the environment, which is usually overlooked in national policies, relates to international impacts. The manufacturing, maintenance and development phases of energy infrastructure are often not fully accounted for in decision-making. This framework puts forward the application of life cycle analysis (LCA) to consider the full range of impacts caused by each stage, from raw material extraction, manufacturing to decommissioning (Chester and Horvath, 2009; Helms et al., 2010; Hawkins et al., 2012; Lovett et al., 2015). This would interlink with on the ground assessments such as Environmental Impact Assessments (EIA) and Strategic Environmental Assessments (SEA) which seek to identify likely significant impacts on the environment from projects such as energy developments (Morrison-Saunders and Arts, 2004).

The impact of an energy transition on employment will also be important to both meeting SDG goals and supporting SLO of transitional energy technologies (Prno, 2013). A key societal impact of the transition to net-zero is the creation of new employment opportunities in various sectors, both through direct and indirect employment effects (Arvanitopoulos and Agnolucci, 2020; IRENA, 2011; Meyer and Sommer, 2014; Cameron and Zwaan, 2015). Using econometric models, such as the one detailed in Appendix Table A.1, the framework can provide quantifiable evidence into how employment will be impacted by an energy scenario (Arvanitopoulos and Agnolucci, 2020).

In addition to employment, public attitudes and SLO of an energy technology will be shaped by engagement with local communities in the decision-making process, the cost of the transition, and how the benefits and costs of the transition are distributed amongst society (Rand and Hoen, 2017). Several studies highlight that energy transitions based on civic ownership of decentralised energy systems could have important implications for the energy democracy of that transition (Becker and Naumann, 2017; Szulecki, 2018). Public support for an energy scenario will also be influenced by the cost of the energy transition, as the cost of electricity and fuel will impact the number of people facing fuel poverty, as well as perceived international social and environmental impacts (Bouzarovski and Simcock, 2017; McCauley et al., 2019). How these impacts are distributed is also likely to influence the SLO of the energy transition (Prno, 2013). The ESE framework offers a range of methodological approaches to determining public acceptance of energy transitions. Decision-makers can measure the socio-political acceptance of an energy scenario using national scale surveys such as the UK Government's Public Attitudes Tracker (Roddis et al., 2019). At the community scale, other means of measuring public attitudes will be needed, with public acceptance 'in the abstract' not necessarily translating to community acceptance 'on the ground' (Buck, 2018). For example, visual impact of wind turbines, closely connected to public attitudes, depends on factors such as how many people can see the turbines, the size of the turbines, the 'naturalness' of the surrounding landscape, and personal preferences (Devine-Wright, 2005). This highlights the importance of a range of factors in public attitudes, and the role of spatial modelling as well as public attitude surveys methodologies.

There are a number of distinct forms of public engagement, referred to as 'ecologies of participation' by Chilvers et al. (2018), and mainstream approaches of societal engagement are often limited in their breadth. It is important to consider the interconnected nature of different collective participatory practices and how the public's attitudes are multi-layered and subject to change over time. As a result of these insights, the ESE framework recommends the use of multiple methods to explore public attitudes and stresses that the outputs from this framework are used as a starting point for discussions with the general public through stakeholder engagement, rather than relying solely on top-down decision-making. The outputs could feed into a 'balance sheet' approach which has been recommended previously to collate, interrogate and present evidence in a pragmatic way (Turner, 2016). Multiple studies emphasise the importance of multi-scalar governance for energy transitions, in which there is scope for national energy scenarios to be translated into action at local and regional levels which are sensitive to context-specific circumstances (Turner, 2016; Essletzbichler, 2012). The complexities of combining the outputs from multiple methods like this to be used in decision-making is explored in Section 3.2.

2.4. *Ex-ante evaluation*

By reflecting upon the outputs from the ex-post evaluation, this framework aims to identify ways in which the creation of energy scenarios could be improved. By soft-linking some of the methods in the framework with energy systems models, a wider range of impacts could be considered when creating energy scenarios. A soft-linking approach capitalises on the strengths of both methods by combining them using an iterative approach, this is preferential to a hard-linking approach which would require the full integration of both models (Krook-Riekkola et al., 2017). The soft-linking approach recommended could have repercussions on the variety of energy mixes proposed by the energy systems models.

Two soft-links are proposed for consideration by this framework. Firstly, hard restrictions on the amount of land that is available for different technologies could be included in energy systems models. The amount of land available could be calculated based upon what is deemed to be socially acceptable (e.g. excluding developments on National Parks or high-grade agricultural land). This would be particularly relevant for bioenergy as there are concerns that the level of land-use required to grow bioenergy crops suggested in some energy scenarios goes beyond what could be socially acceptable (Konadu et al., 2015). Secondly, the distribution of costs for energy technologies indicated by the spatial optimisation methods could be included in the energy systems models. Currently energy system models set costs based upon "today's" cost and the expected trend in costs over time (Ellenbeck and Lilliestam, 2019). These cost assumptions contain a high level of uncertainty for multiple reasons. First, uncertainty is caused by not knowing how manufacturing costs will decrease over time due to technological advancements and economies of scale (Santos et al., 2016). Second, there is uncertainty around how the cost of energy development projects could be influenced by competition for land. So far developments have largely occurred on 'low-hanging fruit' locations, those which are low cost and where conflicts are minimal. However, as more infrastructure is deployed and competition for land increases, most notably in densely populated countries like the UK, energy technologies may have to be deployed to less cost-efficient land (Calvert and Mabee, 2015; Coelho et al., 2012). By including insights from spatial optimisation models regarding how the cost may increase as less optimal locations have to be chosen, this second uncertainty could be reduced. In addition, the costs currently included in energy models only consider market costs (e.g. construction and grid connection costs), they overlook the wider environmental impacts that energy transitions could have including air quality, visual amenity, and soil carbon sequestration implications. A range of ecosystem service costs could therefore be incorporated into energy models to provide an insight into how the scale of renewable energy expansion could impact the natural environment. There are challenges associated with incorporating this type of data into energy models however, such concerns are discussed in Section 3.2.

3. Discussion

The ESE framework provides a holistic assessment of environmental and social impacts of energy scenarios across different spatial scales. As the framework is rooted to the SDGs (Fig. 2), it ensures that the evaluation of energy scenarios does not narrowly focus upon decarbonisation objectives, but instead provides a systematic method to identify and explore the trade-offs and co-benefits between energy goals and the SDG 2030 Agenda (Fuso Nerini et al., 2018). Far-reaching economy-wide change will be required to achieve net-zero transitions and this will be socially disruptive (Miller et al., 2013). A holistic approach to appraising and developing low carbon energy scenarios will be critical to ensuring that these transitions are sustainable and publicly acceptable. In providing this approach, our framework answers the call for the coupling of social and environmental priorities within energy modelling (Hooper et al., 2018). This framework highlights how sustainability and public acceptance should be seen as central, not simply complementary, to achieving net-zero emissions targets by mid-century.

3.1. Strengths of the ESE framework

The ESE framework is advantageous to policymakers because it can be used immediately in net-zero policymaking, alongside existing energy models, and does not require the construction of new models. Net-zero targets require decisive action in this decade and the ESE framework can be used to evaluate energy scenarios alongside the requirements of other policy goals. The methods recommended by this framework, including location-based assessments of the impact of renewable energy expansion, also allow policymakers to explore how trade-offs vary spatially: by using a mixture of methods, impacts at the local, national and global scale can be identified and explored. Using a similar framework which focussed on a subset of SDGs (SDGs 8–10), Patrizio et al. (2020) showed that the impact of energy policy can vary between country, with net-zero transitions leading to economic and employment loss in some countries and growth elsewhere. This sort of analysis can highlight where there may be resistance to energy transitions, and where policy support may be required. The ESE framework can also highlight how methods could be soft-linked to energy system models to broaden the set of impacts considered when creating energy scenarios. For example, the non-market costs of siting energy infrastructure, as estimated by environmental economic models, could be included into energy systems models.

Using a combination of quantitative and qualitative methods the ESE framework allows for a more thorough understanding of the level of public acceptance, taking account of spatial and temporal variations in public attitudes. This part of the framework can be used to support policymakers as they test appropriately for public acceptance at broad national levels, and at the community level, as well as establishing and maintaining a SLO for particular energy technologies and projects, which could help inform decision-making at the national, regional and local levels. 'Community' acceptance describes people's responses to infrastructure at the local level and is not always consistent with the results from national scale surveys (Wüstenhagen et al., 2007; Buck, 2018). Public acceptance at a local level can be influenced by factors such as employment and environmental impact (Healy and Barry, 2017). Roddis et al. (2019), for example, found that support for onshore wind was greater in areas where high levels of people were employed in relation to that technology. Social acceptance can be influenced by a wide range of factors including the perceived visual, noise and biodiversity impacts of the energy infrastructure as well as process-related issues such as the transparency and fairness of the decision-making process (Ellis and Ferraro, 2016). Rand and Hoen (2017) provide an extensive review of wind energy acceptance research highlighting how studies should not view opposition as something to overcome, instead suggesting that individual's concerns should be listened to and not dismissed. They argue that societal acceptance has long been overlooked and it is imperative that socioeconomic impacts, sound and visual annoyance, distributional justice and fairness in the decision-making process are carefully considered. Although economic and natural science modelling can provide some insight into aspects which influence public acceptance like visual impact (e.g. how many people can see a wind farm, willingness to pay to increase the distance between wind turbines and human settlements), they are unable to fully consider the complexities associated with public acceptability of energy transitions across different spatial scales (e.g. the perceived 'naturalness' of the landscape, place attachment) (Devine-Wright, 2005; Rand and Hoen, 2017).

The ESE framework embeds the concepts of the SLO, highlighting the importance of engagement with communities, providing information on impacts of the project, addressing sustainability concerns, and building trust (Prno, 2013). Traditional energy modelling which optimises based on emissions and financial cost is not capable of addressing the requirements of achieving a SLO. Without considering these principles of the SLO, renewable energy projects are likely to face public backlash (Goldthau, 2018). The ESE framework can be used to bring stakeholders into the decision-making process, encouraging societal buy-in by ensuring all voices are listened to (Abram et al., 2020). The framework can provide spatially-explicit information for engagement with local decision-makers and communities to feed into stakeholder engagement activities. The framework promotes the use of qualitative research which can integrate citizen views, attitudes, and values when considering energy transitions. Qualitative research can provide further insights into energy transition discussions, addressing some of the gaps and limitations of quantitative research. Policy is more likely to achieve a SLO when citizens are brought into the decision-making process, shown during the recent climate assemblies in France and the UK (Capstick et al., 2020). These aspects of the framework answer the calls from the 2030 Agenda for greater justice in energy decision-making (Fuso Nerini et al., 2018) and from the Paris Agreement for a just transition to a low-carbon economy (UNFCCC, 2015).

An example of how the ESE framework could be utilised by policymakers is its potential application to the assessment of negative emission technologies (NETs) which are increasingly likely to be required to meet Paris Agreement targets (Rogelj et al., 2018). Whilst technical discussions of bioenergy carbon capture and storage (BECCS) are taking place in policy circles major social barriers to the technologies remain (Fuss et al., 2020; Morrow et al., 2020) and stronger governance structures are called for to promote the SLO (O'Beirne et al., 2020). Trade-offs, as well as co-benefits, between the SDGs and NETs will be context and scale-dependent (Smith et al., 2019). The methodology put forward by our framework can provide holistic and spatially-explicit assessment of the impact of NETs, and employ qualitative research methods to address the existing limited public understanding of the technologies (Cox et al., 2020). Greater understanding of the location-specific impacts of NETs such as BECCS could facilitate public debate and the identification of most suitable locations, increasing the likelihood of achieving a SLO (Buck, 2018).

The ESE framework highlights the challenges and complexities of bringing environmental and societal considerations into energy and decarbonisation policies. Previous models have focused narrowly on evaluating energy scenarios principally upon two metrics: minimising GHG emissions and cost. Whereas identifying environmental and social impacts requires the inclusion of a range of methodologies and the use of a number of different criteria, which leads to disagreement over how best to evaluate these impacts simultaneously. Arguably, the most recent advances in the integration of environmental and social impacts into policymaking have been achieved through the ecosystem service framework, often using monetary valuation, allowing optimisation and clear outputs of policy scenarios (e.g Bateman et al., 2013). We argue that this approach will need to be complemented with more qualitative methodologies which account for winners and losers of particular scenarios if energy scenarios are likely to be sustainable, publicly acceptable and achieve SLO (Peng et al., 2021). Additionally, the 'balance sheet' approach recommended by the UK's National Ecosystem Service Assessment may be a suitable complement to our framework (Turner, 2016; Turner et al., 2014). By using mixed methods, the ESE framework is able to combine the strengths of quantitative and qualitative methods to deepen our understanding of how the energy transition will impact both society and nature (Hussein, 2009; Pluye and Hong, 2014; Lieber and Weisner, 2010). The ESE framework uses a critical interpretive synthesis approach, as defined by Pluye and Hong (2004), to extract concepts from both quantitative and qualitative studies, critically examine these concepts to identify similarities and differences. Although the process of using mixed methods is challenging, it allows researchers to recognise the multiple realities of looking at the same problem (Hussein, 2009).

3.2. Challenges associated with using mixed methods

Some studies have raised concerns with mixed methodologies of quantitative and qualitative research methods. There is a perception that mixing paradigms is problematic because the nuance and detail highlighted by the qualitative data may be lost when insights are drawn more generally (Lieber and Weisner, 2010; Onwuegbuzie and Leech, 2005; Eyisi, 2016). This is one of the reasons why the concept of energy justice has not been embedded directly within the ESE framework. The complexities of assessing energy scenarios in terms of energy justice remains challenging when the paradigm is fundamentally different to the positivist lens used in the ecosystem service approach (Roddis et al., 2018). In this paper, we argue that viewing the ESE framework in parallel to methods which explore energy justice, such as climate assemblies, would be more appropriate. One framework is unable to encapsulate all of the complexities involved in the energy justice paradigm, we would argue that it is possible that no singular framework should try.

A further challenge presented by using mixed research methods is the multiple outcomes that can be observed: corroboration (i.e. the same result), elaboration (i.e. qualitative data analysis exemplifies how the quantitative findings apply in particular cases), complementarity (i.e. results differ but together generate insights) and contradiction (i.e. conflicting results) (Brannen, 2005). When the outcomes of the methods are contradictory, this presents problems when trying to ensure meaningful results are created which can be clearly communicated to a variety of stakeholders (Lieber and Weisner, 2010). Using an interdisciplinary approach to shed light on a complex problem from multiple perspectives is challenging but this does not mean it should not be attempted (Beaumont, 2020). For example, the ESE framework suggests soft-linking the outputs of environmental economic models with energy system models to expand how the natural environment is considered in energy scenario creation. This presents a challenge however, as only certain environmental impacts can be quantified and monetised, and this monetisation provides only a partial value of the impacts (Pearce et al., 2013; Dasgupta, 2021). It would therefore be essential that these insights were only viewed as part of the picture, alongside the insights provided by other methods.

We believe that the ESE framework offers the advantage of bringing together the outputs from multiple methods to allow researchers and policymakers to have discussions across traditional disciplinary boundaries to elaborate on findings, discover contradictions and explore the problem from different perspectives. As other studies have highlighted already, mixed methods can increase the credibility of scientific knowledge and perform an important role in informing policy (Hussein, 2009; Pluye and Hong, 2014). The question of whether an energy scenario is likely to achieve public acceptance and sustainability is one that cannot be explored using one method or one paradigm, it is a question which needs different perspectives and understandings. We agree with the use of a 'jigsaw of evidence' (O'Sullivan and Howden-Chapman, 2017): bringing together multiple findings to create valuable policy relevant information.

4. Conclusions

A whole-systems approach is essential to assess how the transition to a low carbon energy system may impact the economy, environment, and society. A wide range of methodological approaches are required to ensure all aspects of the transition are covered, however, historically the differences in a mixed methods approach across disciplines has made this whole-system approach difficult to achieve. The need for interdisciplinary and transdisciplinary approaches has been recognised as vital to tackling the world's current global environmental challenges, with the decarbonisation of energy systems one such challenge (Sovacool et al., 2015). The ESE framework outlined in this paper reflects the broad range of approaches that can be taken to evaluate energy scenarios in terms of their sustainability and public acceptability. In assessing how different methods can be used to complement each other, this paper has explored practical ways in which decision-makers can use multiple methods to evaluate transformative changes to an energy system.

As countries across the world transition to low carbon economies, new energy infrastructure will need to be constructed, and a strategy employing multiple research methods will be needed to achieve the objectives of the SDGs including: GHG reductions, low financial cost, environmental protection, job creation and public acceptance. This paper shows how multiple methods can be used together to improve integrated approaches for assessing energy scenarios considering impacts at different spatial scales. Overall, we propose the ESE framework can be used to support decision-makers evaluating the financial, environmental, political and social feasibility of energy scenarios, thereby contributing to the pursuit of realistic, deliverable and sustainable decarbonisation goals.

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CRediT authorship contribution statement

Gemma Delafield: Conceptualization, Methodology, Investigation, Writing – Original draft preparation, Writing – Review & Editing, Visualization. **Caspar Donnison:** Conceptualization, Methodology, Investigation, Writing – Original draft preparation, Writing – Review & Editing. **Philippa Roddis:** Conceptualization, Methodology, Writing – Original draft preparation, Writing – Review & Editing. **Theodoros Arvanitopoulos:** Methodology, Writing – Review & Editing. **Alexandros Sfyridis**: Methodology, Writing – Review & Editing. **Sebastian Dunnett:** Methodology, Writing – Review & Editing. **Thomas Ball:** Methodology, Writing – Review & Editing. **Kathryn G. Logan:** Conceptualization, Methodology, Investigation, Writing – Original draft preparation, Writing – Review & Editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

See Appendix Table A.1.
*

Table A.1
Overview of suggested methods and how they apply to the framework.

Method	Description	Framework application*
Spatial optimisation	The ADVENT-NEV (Delafield et al., unpublished) and BECCS optimisation models (Donnison et al., 2020) use spatial optimisation techniques to identify the least cost locations for new solar farms, wind farms, bioenergy power stations and/or BECCS. These models optimise both market (e.g. construction and opportunity costs) and non-market costs (e.g. visual impact and carbon sequestration) to determine the financially or socially optimal spatial distribution of energy infrastructure.	
Random forest	The random forest potential (RFP) probability surfaces developed by (Dunnett et al., unpublished) identify where new solar and wind farms are most *likely* to be located in the future based upon existing locations of energy infrastructure and environmental impacts including biodiversity. The model was developed using existing locations of wind turbines and solar panels identified with OpenStreetMap in Dunnett et al. (2020).	
Inferential logistic regression	Logistic regression can be inferentially used to show where infrastructure is more or less likely to be accepted based upon historical planning acceptance (Roddis et al., 2018). Trends in planning acceptance is an indicator of how communities feel about energy developments and therefore can be analysed to consider how acceptable energy scenarios might be in terms of deployment 'on the ground'.	
Regional box model	A regional box model is being developed to assess the location and quantity of land available for BECCS globally (Ball et al., unpublished). The model considers how the availability and suitability of land for BECCS is driven by a range of factors, including food system efficiency, dietary trends and sustainable governance. The model can determine the global sustainability implications of importing biomass from specific countries by combining metrics for environmental governance and political stability.	
Viewshed analysis	The visual impact of an energy scenario can be assessed using viewshed analysis: a Geographic Information System technique which calculates the area (i.e. viewshed) where an object is visible, taking into account the height of the object and the intervening terrain (Carver and Markieta, 2012; Wen et al., 2018). Viewshed analysis can be applied at local or national scales to estimate the visual impact of different low carbon energy scenarios.	
Data mining and machine learning algorithms	By estimating traffic flows for any given point on the road network, air pollution across the UK at a street level can follow. Sfyridis and Agnolucci (2020) have developed a model to estimate traffic volumes on a street segment level using a hybrid clustering-regression approach, while the follow up research by Sfyridis and Agnolucci (2021) determines the spatial distribution of GHGs and air pollutants using a probabilistic classification-regression model. The model estimates air pollution using assumptions from the COPERT model (Ntziachristos et al., 2009). Traffic flows are estimated using: traffic count points from the UK's Department for Transport, the K-prototypes clustering algorithm, and random forests, OLS and support vector regression.	
Panel regression analysis	Agnolucci and Arvanitopoulos (2019) have developed a method to assess how emissions from the manufacturing sector have changed over time using panel regression analysis. This information can be used to check whether the elasticities estimated by Agnolucci and Arvanitopoulos (2019) and Agnolucci et al. (2017) can be used to calibrate the economic models that generate energy scenarios.	
OPerating Emissions Model	The operating emissions model (OPEM) is a deterministic model developed to project operating emissions through a series of different conventionally fuelled vehicles and electric vehicles integration scenarios. Input data for this model can incorporate different energy scenarios. The OPEM is a simple model and easy to manipulate and comparable and is easier to use when comparing countries (Logan et al., 2020a, 2020b, 2020c, 2021).	
Life cycle analysis (LCA)	LCA can provide an insight into the environmental implications of a shift to low-carbon electricity supply by considering the manufacturing and material life of energy technologies (Hertwich et al., 2015). Stamford and Azapagic (2014) provides an example of applying LCA to a UK energy scenario.	
Vector Auto- regressive Model	An empirical methodology, based on econometric methodology such as Vector Autoregressive Model (VAR), can be used to quantify the potential employment impact from the deployment of renewable energy technologies (Arvanitopoulos and Agnolucci, 2020). This method can, therefore, be used to estimate the expected number of jobs generated (or lost) related to a specific energy scenario.	
Regression analysis of public attitudes	A regression model using data from the UK Government's Energy and Climate Change Public Attitudes Tracker (PAT) was developed to understand the drivers of positive and negative attitudes towards energy technologies (Roddis et al., 2019). The results of this regression model and other similar analyses of public attitudes could be used to gain insight into how different UK low carbon energy scenarios may be regarded by the public on a national scale.	

(continued on next page)

Table A.1 (*continued*)

Method	Description	Framework application*
Balance sheet approach	The Balance Sheet Approach (BSA) can be used to build an evidence base to support decision-making. The framework provides an approach to collect, analyse and present data which considers the distributional impacts of the costs and benefits of an intervention (Turner, 2016; Turner et al., 2014).	  

depicts methods which relate to where energy infrastructure will be located,

relates to natural environment impacts,

sectoral impacts,

public opinion and

employment.

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